

Standard Model Higgs Searches at the LHC

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An overview of the searches for the Standard Model Higgs boson at the LHC is presented. The main Higgs production and decay modes that have been studied are introduced, and the analysis techniques and the recent developments done by the ATLAS and CMS experiments are described. Some preliminary results from current studies are included. The discovery potential within the first few years of physics running is evaluated.

1. Introduction

The Large Hadron Collider (LHC) will enable production of the Standard Model Higgs boson in the entire range of its allowed mass; from the lower experimental exclusion limit of $114.4 \text{ GeV}/c^2$ [1] to the theoretical limit of $1 \text{ TeV}/c^2$. An early discovery of the Higgs boson is the primary objective of the two general purpose detector experiment, ATLAS and CMS. The search requires a good understanding of both the data and the physics of the background processes, and extensive studies based on MC simulation are being carried out by both experiments to prepare for the analysis of the LHC data. Over the past years, the analyses have constantly been improved. New event generators and more precise description of the detector in the simulation are employed, and more sophisticated analysis techniques and tools are being developed.

In this paper, an overview of the activities within the ATLAS and CMS collaborations towards the discovery of the Higgs boson at the LHC is presented. This includes basic ideas and the particular challenges, as well as some of the new developments and recently updated results for the main channels studied. Many of the analyses are targeted towards the first year to 3 years of physics runs where a low luminosity ($L = 2 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$) environment is assumed. Both experiments are currently undertaking a major update of the analysis results, many of which are unavailable at present, however, new results are expected to be made public in the near future before the arrival of the LHC physics data. The prospects for the Higgs searches in the early years of LHC operation including all the channels introduced here are summarised at the end.

2. Higgs at the LHC

The most dominant mechanism for the production of the Higgs boson at the LHC is the gluon fusion, followed by the Vector Boson Fusion (VBF) which is approximately an order of magnitude smaller in cross section (Fig. 1 (a)). While inclusive searches have the advantage of having a large cross section, the VBF or other production mode specific studies are also carried out by the ATLAS and CMS experiments to improve the sensitivity of the search by exploiting the additional signatures in the final state. If the Higgs boson mass is below $130 \text{ GeV}/c^2$, the main decay modes are $b\bar{b}$ and $\tau\bar{\tau}$ (Fig. 1 (b)). These are also the challenging channels due to the presence of hadronic decay and the relatively small p_T involved in the final state particles. The $H \rightarrow \gamma\gamma$ decay mode, on the other hand, provides a clean signature of high p_T photons which can be well reconstructed, hence plays an important role in the Higgs searches at the LHC. For the higher Higgs mass region, the decays to the vector bosons, W and Z , are the dominant channels. Both ATLAS and CMS detectors were designed to deliver the optimal performance for the observation of these benchmark channels.

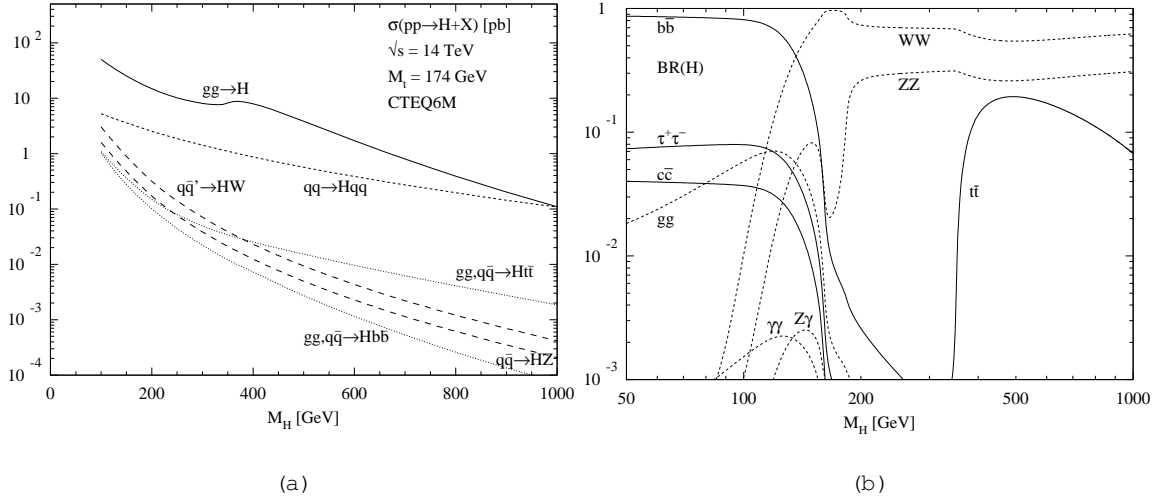


Figure 1: (a) The Standard Model Higgs boson production cross section expected at the LHC and (b) the Higgs decay branching ratio as a function of its mass.

3. Low Mass Higgs Searches

3.1. $H \rightarrow \gamma\gamma$

The Higgs decay to a photon pair is one of the most promising channels for an early discovery of the Higgs boson in the low mass range, despite its small branching ratio and the large background contributions expected. The dominant background to this channel with two real photons arises from the prompt diphoton production. Additionally there is a large contribution from the so-called instrumental background, which are gamma + jet or multi-jet events where one (or two) jet is misidentified as a photon. The Higgs boson signal would appear as a resonance peak in the distribution of the invariant mass of the two photons ($M_{\gamma\gamma}$) above the background continuum. Figure 2 (a) shows the reconstructed diphoton mass distributions for background and signal processes with different mass scenarios in an inclusive search [2]. The background contributions in the signal region are estimated from the side bands of the $M_{\gamma\gamma}$ distribution.

The narrow width of the signal mass peak is the key to observing such events over a large background, and an excellent electromagnetic (EM) calorimeter resolution is crucial. Both ATLAS and CMS detectors have been carefully designed to detect this one of this benchmark channel, and to maximise their performance the calibration of the detector during the early years of data taking become important tasks. For the CMS experiment, various methods have been developed for the intercalibration of the uniformly distributed lead tungstate crystals in the EM calorimeter to achieve the design goal resolution of less than one percent at high energy. The instrumental background contributions are largely reduced by applying a tight tracker isolation and selection based on the shower shape variables upon photon selection. A significant fraction of the photons convert before reaching the calorimeter due to the material in the central detector; a further signal yield can be obtained by identifying and recovering these converted photons. Complementary to the lateral shower shape, ATLAS also uses the longitudinally segmented information of the energy deposition in the EM calorimeter to identify the fakes and converted photons.

Both experiments employ multivariate techniques, such as likelihood and neural network, to increase the sensitivity of the search. The inputs to obtain the final multivariate discriminant include those variables developed for photon identification and those based on the event kinematics: e.g. p_T of the diphoton system

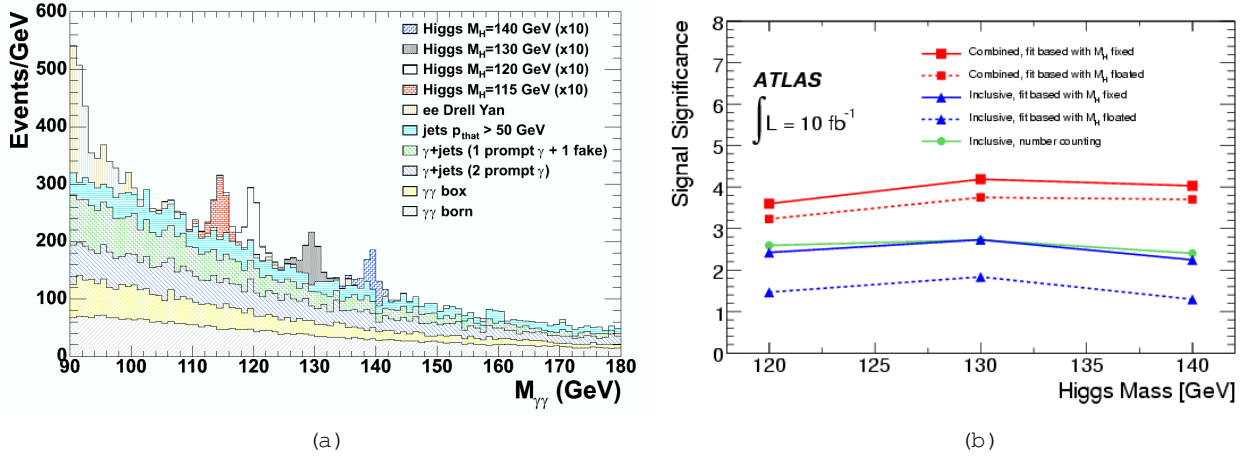


Figure 2: (a) The invariant mass reconstructed from two high pt photons for the inclusive $H \rightarrow \gamma\gamma$ analysis for a simple cut based analysis before optimisation done by CMS. Different background contributions and signal events with 4 different masses are shown. (b) The statistical significance of the observed events that can be achieved at an integrated luminosity of 10 fb^{-1} , which corresponds approximately to one year of data-taking at low luminosity of $2 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. A comparison is made between the inclusive searches and the combined results from categorised optimisation.

and the photon decay angle¹. For a further optimisation, events are categorised depending on the detector region, photon shower shape, jet multiplicity etc. Recent ATLAS studies show that the signal significance can be improved by a factor of 1.5 or more by combining the categories which are separately analysed and optimised (Fig. 2 (b)) [3].

3.2. $qqH, H \rightarrow \tau\tau$

The hadronic decay of tau lepton is distinct from a jet; its final state contains a limited number of charged particles (1 or 3 tracks considered for the majority of the analyses) which are relatively collimated, forming a narrow energy deposition in the calorimeters. The Higgs decay into two taus becomes a powerful channel when combined with the Vector Boson Fusion (VBF) production. In addition to the Higgs decay signal of leptons (electron/muon) and/or hadronic taus, properties of two very forward out-going quarks from the VBF process provide further discrimination against other Standard Model processes. The most dominant background to this channel is the $Z \rightarrow \tau\tau$ with associated jets, which are mostly produced via QCD processes involving gluons. The signal VBF events can be distinguished from those $Z + \text{jets}$ background since the two leading quark jets are well separated in pseudorapidity, and the hadronic activity in the central region is heavily suppressed due to the colour coherence of the initial and final state radiation from each of the quarks. The event selection is mainly based on the VBF jets: kinematics of individual jets and angular separation and invariant mass of the di-jet system. The selection cuts based on the VBF jets are equally effective against various instrumental/reducible backgrounds such as $W + \text{jets}$, multi-jet and $t\bar{t}$ events, and their contributions can be reduced by orders of magnitude. In addition, events with central hadronic activities (jets and/or tracks excluding those from leptons or hadronic tau) are vetoed for a further reduction of background events by a factor of two while maintaining 90% signal efficiency [4].

¹ the variable used is $\cos \theta_{\gamma\gamma}$, where $\theta_{\gamma\gamma}$ is the photon decay angle in the Higgs rest frame with respect to the Higgs flight direction in the lab frame.

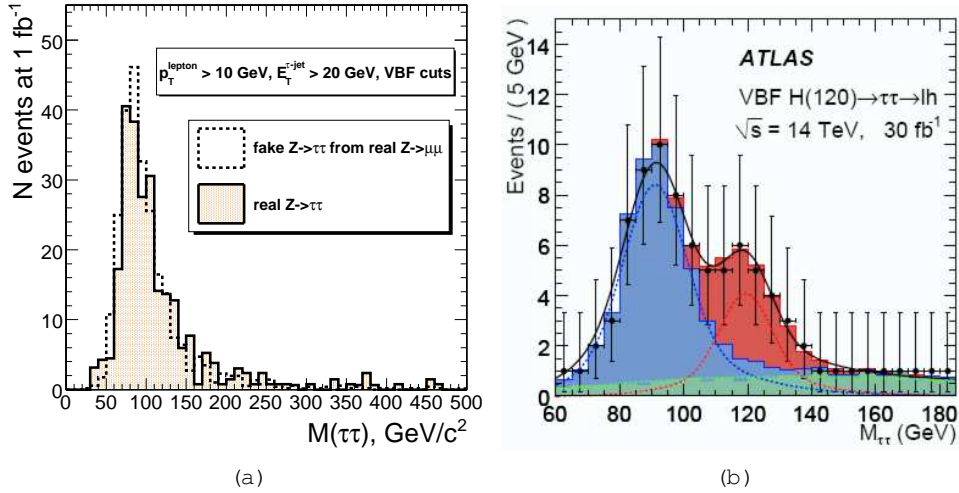


Figure 3: (a) Demonstration of $Z \rightarrow \mu\mu$ mass shape estimation using $Z \rightarrow \mu\mu$ events done by CMS. A relaxed set of cuts are applied on the leading VBF jets, assuming the data in the 1st year of physics runs at the LHC. The fake (modeled) M distribution is in good agreement with the real $Z \rightarrow \mu\mu$ events. (b) The full invariant mass of two taus reconstructed using collinear approximation for the $H \rightarrow \tau\tau \rightarrow lh$ (one tau decaying leptonically and the other hadronically) channel (ATLAS). The M distribution is shown for the mass of 120 GeV/c^2 and the events are normalised to the number expected to be observed after all selection cuts at 30 fb^{-1} of data, which can be collected in 3 years at low luminosity. The mass shape is fitted with signal + background hypothesis.

The mass of the Higgs boson cannot be directly reconstructed for the $H \rightarrow \tau\tau$ channel because of the neutrinos involved in the tau decays. A collinear approximation is used to first reconstruct the full tau lepton energy by projecting the missing E_T to the direction of the visible decay products, and then to calculate the mass of the Higgs boson as the invariant mass of the two tau leptons. Missing E_T reconstruction involves various parts of the detector thus a challenging variable to measure at hadron colliders, and some inefficiency from this method is expected for events with poorly reconstructed missing E_T . However, the collinear approximation also effectively removes a large fraction of those background processes with no/small missing E_T such as $Z \rightarrow ll$ ($l = e/\mu$) events. It is important to precisely model the shape of the $Z \rightarrow \tau\tau$ mass distribution, especially if the mass of the Higgs boson is relatively small that the M resonance peak would appear near the Z mass. It has been proposed to use the $Z \rightarrow \mu\mu$ data replacing the detected muons by the simulated tau decays, such that the rest of the events (associated jets, minimum bias, underlying events, etc.) are the same as that in data (Fig. 3 (a)) [4]. The $Z \rightarrow ee$ background with electrons mis-identified as hadronic taus is particularly a dangerous background in the expected signal region. A dedicated variable is developed to reject electrons which is otherwise identified as hadronic taus, and their contribution is planned to be estimated from data by using inverted cuts [4].

An example of the invariant mass distribution of the selected signal and background events is shown in Figure 3 (b) after all the selection cuts are applied [3]. The Higgs boson signal is clearly visible on the high mass tail of the Z mass distribution, and the rest of the background is expected to be flat over the mass range concerned. The events are normalised to the statistics expected at the integrated luminosity of 30 fb^{-1} , equivalent to the kind of time-scale that a 5 σ discovery is expected to be within the reach for both ATLAS and CMS.

3.3. $t\bar{t}H$, $H \rightarrow b\bar{b}$

The Higgs decay to bottom quark pair has the largest branching ratio at low mass. At the same time, it is a very challenging channel to observe due to its hadronic final state. Jets originated from b-quarks differ from those from light quarks in characteristics such as charged particle multiplicity and secondary vertex displacement,

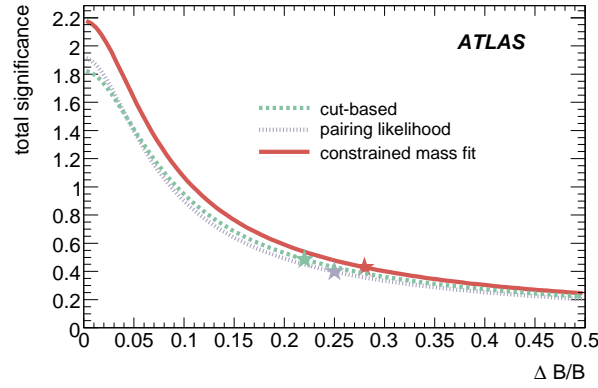


Figure 4: The signal significance in terms of number of sigma that can be achieved for the search of $ttH \rightarrow ttbb$ process shown for different level of uncertainty (ΔB) on the number of background events (B). An integrated luminosity of 30 fb^{-1} is assumed.

hence a moderate level of background rejection can be achieved by tagging these b -jets. Nonetheless, the background rate is still high due to the high cross section of multi-jet events at the LHC. In addition, the di-jet mass resolution is less defined compared to the mass reconstructed from leptons because the energy and position resolution of a jet is generally much worse than the lepton resolution. For this decay channel, a production via tt fusion has been considered by both experiments to increase the background rejection power. The weak decay of the top quarks produces additional b -jets, and the leptonic and/or hadronic decay of the W bosons also helps to signify the signal process. The high jet (b -jet) multiplicity and a presence of a lepton reduce the instrumental background to a negligible level, and the dominant background becomes the $ttbb$ production which has a cross section an order of magnitude higher than that of the ttH Higgs production. The final state with four b -jets introduces a combinatorial background where a wrong b -jet pair may be associated to the Higgs decay, which is an additional complication to the analysis of this channel.

Due to the large theoretical uncertainty on the background cross sections, their contributions are planned to be estimated from data. The shape of the b -jet invariant mass distribution is extracted from the loosely selected samples, and the absolute normalisation is obtained from the side-bands in the final selected sample of events. The control of the experimental uncertainties is a major task; the largest sources of uncertainties are the jet resolution, jet energy scale and b -tagging efficiency. Figure 4 shows the signal significance that can be achieved as a function of the uncertainty on the number of background events [3]. It illustrates that the systematic uncertainty needs to be understood to a level of few % in order to claim greater than 1 significance at integrated luminosity of 30 fb^{-1} after few years of low luminosity run.

4. Higher Mass Higgs Searches

4.1. $H \rightarrow WW$

The $H \rightarrow WW$ process becomes most significant in the intermediate mass region when the Higgs boson is heavy enough to produce the W bosons on-shell. The discovery reach can be further extended by performing a dedicated search for the Higgs production via Vector Boson Fusion where additional background suppression can be achieved. The leptonic decay of the W bosons is favoured for triggering reasons as well as the level of the background contributions expected at the LHC. However, the involvement of neutrinos in the W decay makes the analysis less straightforward. Due to its heavier mass, those neutrinos will not be collinear with

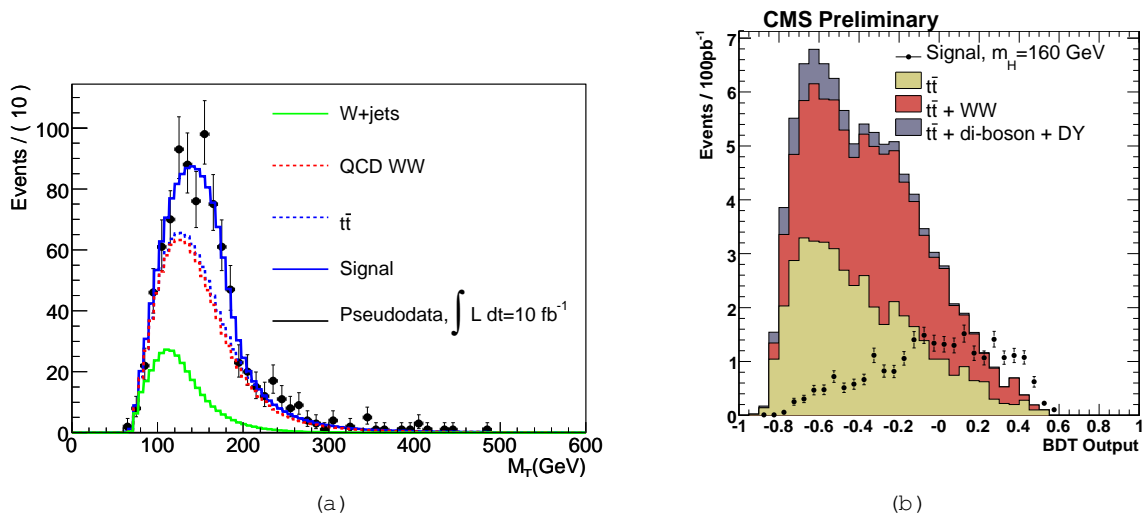


Figure 5: (a) The transverse mass distribution in the signal region of $m_{ll} < 1.575$ (ATLAS). The distribution for the signal and background MC events are shown with superimposed pseudodata which are generated for an integrated luminosity of 10 fb^{-1} . (b) The output of the Boosted Decision Tree for the Higgs signal with a mass of $160 \text{ GeV}/c^2$ and various background processes. The events are normalised to 100 pb^{-1} of integrated luminosity, which corresponds to the data that can be collected in the first months of the physics data taking at the LHC.

the leptons as demonstrated for the $H \rightarrow WW$ analysis, hence it is almost impossible to reconstruct a well defined mass peak. The $H \rightarrow WW$ search is therefore performed as a counting experiment, where a precise knowledge of the background contents in data is crucial.

The single most powerful discriminant for the $H \rightarrow WW$ channel is the separation of the two leptons from the W decays. Compared to the dominant WW background from the continuum $q\bar{q} \rightarrow WW$ and $t\bar{t}$, the W boson (hence the decay leptons) are strongly spin-correlated in the signal process since they decay from a single Higgs boson with a spin of zero. This gives rise to a relatively small angular separation between the final state leptons contrarily to the background WW production. The events in the high m_{ll} region (control region) can be used to model the background and to estimate their contributions in the signal region. Other variables used for the $H \rightarrow WW$ search include dilepton mass, WW transverse mass and missing E_T . For the exclusive search for the VBF production, similar cuts on the kinematic variables based on VBF jets which are introduced for the $H \rightarrow WW$ analysis (Section 3.2) are used. Central Jet Veto is as effective for the inclusive search to reduce the $t\bar{t}$ background contributions. In the past studies, different set of selection cuts are applied and/or relaxed/inverted in order to separately estimate the different background contributions (for e.g. [5]).

The signal and background contents in the signal region of small di-lepton separation are shown in the transverse mass distribution after selection cuts are applied in Figure 5 (a) [3]. Already at 10 fb^{-1} , a significant excess from the $H \rightarrow WW$ signal is expected to be observed at the level of tens of % of the number of estimated background events from other Standard Model processes. A sizable systematic uncertainty of 15% arises from the background estimation, and it may increase up to 50% with very early data due to the limited statistics. The multivariate techniques are used to increase the sensitivity of the search at the relatively early stage of the physics runs. Figure 5 (b) shows an example of the output from a multivariate analysis using Boosted Decision Trees (BDT). Several kinematic variables including m_{ll} are used as the inputs to the BDT [6]. A moderate separation between the signal and the background events is achieved, enhancing the signal significance in the positive output value. A correct usage of multivariate tools requires sufficient understanding of all the input variables, and a good description of the background distribution in variables involving jets and missing E_T remains an important task.

4.2. H! ZZ

The H! ZZ decay is often referred to as the "Golden Channel" at the LHC because of its very clear signature of multiple high p_T leptons (electron/muon) without any hadronic objects or missing E_T involved in the final state. This decay mode has a significant advantage over other channels in terms of branching ratio at high mass, and the sensitivity of the search is further enhanced by the relatively small background contributions. Both ATLAS and CMS detectors are designed to deliver an excellent electron and muon identification and reconstruction performance for this benchmark channel. A particular effort has been put into the reconstruction of low p_T leptons down to few GeV/c in order to access the low mass region.

The event selection is mainly based on the lepton quality and kinematics. The vertex information is used to reconstruct the invariant mass of the leptons. The dominant sources of background to the 4-lepton signal are the Zbb, tt and ZZ production. Some of the leptons in the Zbb and tt processes are produced with b-jets and can be suppressed by requiring a tight isolation on these leptons. A further reduction of the background is achieved by associating the leptons to Z. The oppositely charged leptons are paired and their invariant mass is required to fall within the Z mass window. The best pairs are used for 4e and 4 μ channels where more than one combination is possible. The contributions from the remaining ZZ background is planned to be obtained from data: either by fitting the known ZZ shape to the sidebands of the 4-lepton invariant mass distribution or by normalising it to the cross section predicted by the single Z production cross section. The former method can achieve better precision when there is sufficient statistics of data, however, in the early period of data-taking when the discovery of the Higgs boson through this channel is already possible it suffers from a large statistical uncertainty. For the second method, the Z production cross section can be measured to a precision at an integrated luminosity of the order of 10 fb^{-1} . Taking the ratio to the ZZ cross sections cancels out some of the theoretical and experimental uncertainties. The overall uncertainty on the background events for both methods is expected to be at the level of few %.

The reconstructed invariant mass of the four leptons is shown in Figure 6 (a) after the selection for a generated Higgs mass of $150 \text{ GeV}/c^2$ [3]. The events are normalised to the expected number of events at the integrated luminosity of 10 fb^{-1} . In this relatively low mass range, the ZZ background level is very low since the production of real (on-shell) Z boson pair is suppressed below the threshold of twice the mass of Z. Figure 6 (b) shows the M_{4l} distribution normalised to the statistics needed to achieve 5 σ discovery for a high mass Higgs boson of $200 \text{ GeV}/c^2$ [7]. The particular decay mode of ZZ! ee has advantages over the 4e or 4 μ channels by the fact that the branching ratio is doubled. It also benefits from the absence of the combinatorial background since the leptons can be only paired within the same flavour. For both plots of the 4-lepton invariant mass distribution, the higher order corrections are applied to the background cross section.

5. Discovery Potential

The Higgs boson discovery reach of the ATLAS and CMS experiments at the integrated luminosity of 30 fb^{-1} are summarised in Figures 7 (a) and (b) for the entire range of Higgs boson mass discussed [8] [7]. For ATLAS, the low to intermediate mass range is well covered by the H! and H! WW decay channels combined with the Vector Boson Fusion production, reflecting the strength of the ATLAS detector in the jet and missing E_T reconstruction. On the other hand, the H! decay channel is most promising for CMS where it benefits from the high performance EM calorimeter, and can achieve 5 σ significance at Higgs masses down to $110 \text{ GeV}/c^2$. The two experiments provide similar performance in the high mass region, and ATLAS further extends the reach by including the VBF production process. With 30 fb^{-1} of data, the discovery of the Higgs boson is possible for all the mass range up to the TeV scale by each of the experiments alone. There has not been a recent combination of results, however, with ATLAS and CMS together the early discovery is within the reach.

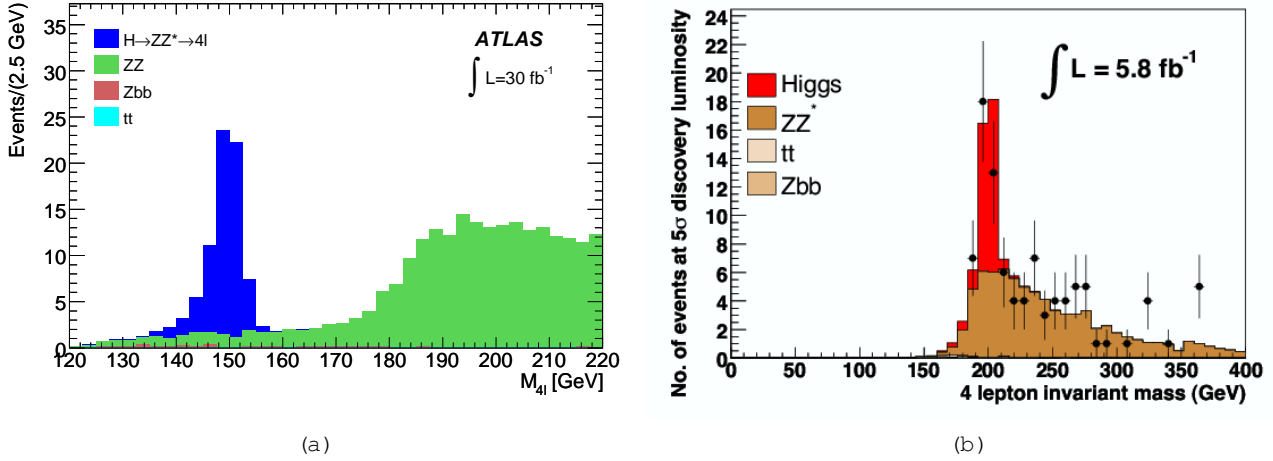


Figure 6: (a) The invariant mass of the four leptons for a Higgs mass of $150 \text{ GeV}/c^2$. For the signal process, one of the Z boson is produced on-shell. The events are normalised to an integrated luminosity of 10 fb^{-1} , which corresponds to one year of low luminosity run. (b) The M_{4l} distribution for the $H \rightarrow ZZ \rightarrow ee$ channel with the statistics need for 5 discovery (CMS). The MC signal and background processes are shown with pseudo data randomly generated according to the predicted distribution.

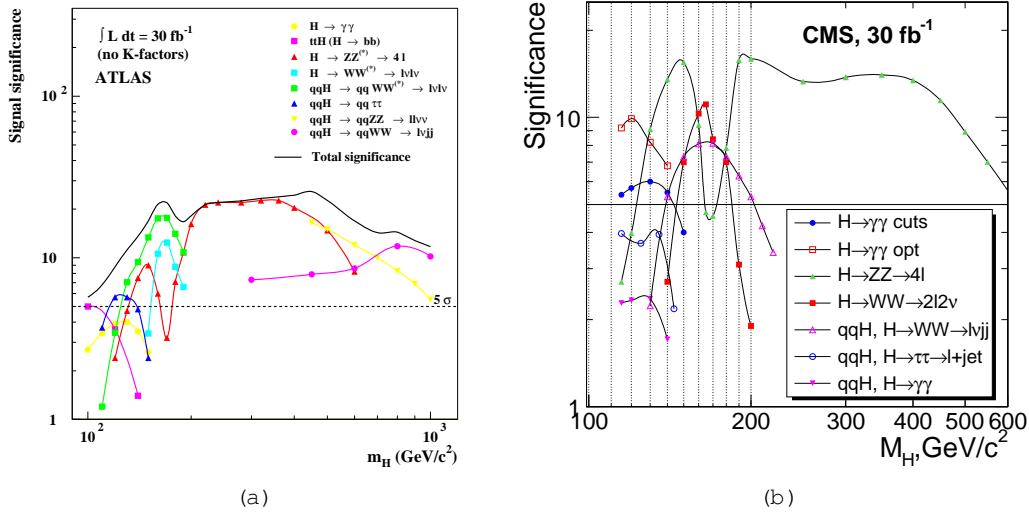


Figure 7: The significance of the signal events expected to be observed by the (a) ATLAS and (b) CMS experiments for a range of Higgs boson mass with an integrated luminosity of 30 fb^{-1} , which corresponds to 3 years of data taken with the low luminosity runs ($L = 2 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$).

6. Summary

The prospects for the Standard Model Higgs boson search at the LHC have been presented. A wide range of Higgs production and decay channels are studied by the two general purpose detector experiments, ATLAS and CMS, and the results show that the discovery would be possible for all the mass range already in the first year or two of physics data. There are continuing efforts to improve the analyses and to be ready for the first physics data at the LHC expected in the coming year.

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